PROCEEDINGS OF THE

PARTICLE BEAM RESEARCH WORKSHOP

U.S. AIR FORCE ACADEMY

10-11 JANUARY 1980

MAY 1980

OFFICE OF THE UNDERSECRETARY OF DEFENSE
RESEARCH & ENGINEERING
WASHINGTON, D.C. 20301

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON D.C. 20301

RESEARCH AND
ENGINEERING

7 MAY [illegible]

MEMORANDUM FOR THE DEPUTY UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING (RESEARCH AND ADVANCED TECHNOLOGY)

SUBJECT: Particle Beam Research Issues

The Air Force Academy Particle Beam Workshop was stimulated by the Research Office to provide an unclassified forum for the discussion of research issues relevant to charged particle beam technology. The Army Research Office and the Air Force Office of Scientific Research jointly sponsored workshop not only drew heavily on scientists and engineers already engaged in this area of research and technology but also included a cross section of workers who may be able to contribute fresh approaches to this technology.

The attached Proceedings is a survey of research issues that was written by the workshop participants during this two-day meeting. It is significant as a research guide to potential new performers who desire orientation to the subject and to the various managers that are engaged in the management of particle beam and related technologies within the Department of Defense.

It is fitting that the Army Research Office and the Air Force Office of Scientific Research have accomplished the organization of the workshop and the publication of these Proceedings. These agencies are the primary points of contact of these two Services with the at-large scientific community, from which fresh innovations may be expected in particle beam research and technology.

This report has been studied by the Research Office, and I recommend it to you for your consideration.

George Gamota
Director for Research

Attachment

cc:
Dr. Fossum, DARPA
Dr. Airey

1 MAY 1980

MEMORANDUM FOR DIRECTOR FOR RESEARCH

SUBJECT: Particle Beam Research Issues

We are pleased to submit to you a survey of research issues relevant to particle beam technology. This survey was based on the workshop held at the Air Force Academy on 10 and 11 January 1980. It reflects intensive examination of the technology by over 130 of the nation's leading scientists and engineers engaged in particle beam and related research.

It is recognized that it is not possible to elaborate all of the research needs associated with a complex technological system such as a particle beam weapon. Furthermore we cannot anticipate new opportunities that will arise from present and future research, sometimes pursued with quite different motivation than particle beam weapons.

Nevertheless this report provides for the first time an unclassified guide to some of the major issues that are perceived to be relevant to particle beam technology. It was generally recognized by the workshop attendees that there is a need for the fresh approaches that would be provided by "new performers". This document should provide those research workers who do not have access to classified information with an initial guide to the field.

We are indebted to the workshop participants for the enormous cooperation we received.

Hayes R. Bryan

HAYES R. BRYAN
Colonel USAF
Director
Physics and Geophysics
Air Force Office of
Scientific Research

Robert Lontz

ROBERT LONTZ
Director
Physics Division
Army Research Office

ISSUES IN UNCLASSIFIED

PARTICLE BEAM RESEARCH

Prepared by

(10) B. D. Guenther
Robert Lontz
US ~~Army Research Offic~~e

John L. May
Air Force ~~Office of Scientific~~ Research

C. Martin Stickley
The BDM Corporation
With Support From
Battelle Columbus Laboratories
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on 10-11 January 1980,

This document was prepared for the Office of the Director for Research, Office of the Under Secretary for Defense for Research and Engineering for the purpose of providing information on DoD needs in particle beam research. Comments regarding this document or suggestions for improvements in further editions should be forwarded to:

Director for Research
OUSDRE(R&AT)
Washington, D. C. 20301

APPROVED FOR PUBLIC RELEASE

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PREFACE

This report constitutes the proceedings of the Particle Beam Research Workshop sponsored by the US Army Research Office and the Air Force Office of Scientific Research, and held at the US Air Force Academy, Colorado Springs, Colorado, on 10 and 11 January 1980.

The Introduction and Summary was prepared by B. D. Guenther and R. Lontz of ARO and J. L. May of AFOSR with the assistance of the Executive Committee.

The remaining five chapters of this report were prepared from materials developed by the workshop participants. They were assembled and edited by C. M. Stickley of The BDM Corporation, McLean, Virginia, with the support of the Scientific Services Program, Durham Operation, Battelle Columbus Laboratories. He was assisted in this by D. Wunsch and B. J. Eastlund of BDM, P. Grand of Brookhaven, and R. O'Rourke, a consultant to BDM.

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I. INTRODUCTION AND SUMMARY

1.1 Introduction

The particle beam research workshop was jointly organized by the Army Research Office (ARO) and the Air Force Office of Scientific Research (AFOSR) to develop a forum for the discussion of unclassified research issues relevant to particle beam weapons technology. It was an additional objective to develop a document which could be used as an unclassified guide for scientists who are interested in this technology but have not had prior access to the classified efforts. Finally, the workshop and the guide are designed to provide an information resource for DoD managers concerned with the opportunities that unclassified research offer to this technology.

The workshop was opened with overviews of the DoD's interest in particle beam research and development by Dr. George Gamota, and a perspective on the viability of particle beams as a weapon by Dr. John Parmentola of MIT (see John Parmentola and Kosta Tsipis, "Particle Beam Weapons", Scientific American 240 (4) 54, April 1979). These were followed by invited presentations in each of the five areas which defined the working panels of this meeting: Power Generation and Conditioning; Sources and Injectors; Accelerators; Propagation; Beam/Material Interactions.

Following all of the invited presentations, the participants joined the five working panels and were charged with producing statements of issues appropriate for unclassified research (DoD 6.1 funding category). The chairman of the five panels were instructed that the objective was to develop issue statements as distinct from a tutorial or a research plan. The workshop was concluded on the second day afte each of the chairman summarized the findings of the panels before an assembly of the entire workshop.

An executive committee subsequently met to further organize the workshop material cn which to base a report which would not exceed ten pages. This Introduction and Summary constitute that report. It is followed by five chapters providing a more detailed description of the products of the five panels.

The workshop proceedings were strongly constrained in several ways to ensure that the objectives of the ARO and AFOSR would be met. Attendance was by invitation only in order to control the workshop size which, in spite of the lack of advertising, grew to over 100. The invitations extended primarily to the classified technology community and, to a less degree, potential new performers from the larger science population. Both of these communities could have been more extensively represented, and this placed a constraint on the proceedings and this report.

The workshop attendees were also given a very limited time in which to deliberate, approximately one working day. This time constraint was very stringent but designed to ensure that a product would result before the participants left Colorado Springs. Finally, the proceedings were limited by the fact that no classified results were discussed.

1.2 Power Generation and Conditioning

Adequate power generation and conditioning are important requirements for all high peak power accelerator systems and their auxiliaries. Advances in the state of the art are essential for the development of a particle beam technology base as well as in design of eventual weapons systems. Furthermore, related technologies such as inertial and magnetic confinement fusion, radiation simulation and lasers have critical pulsed power requirements. Significant requirements for broad based research exist in the following subareas.

- Switching. New closing switch concepts with improved repetition rate, voltage and current capabilities are among the major determinants in developing accelerator designs. Concepts for both low and high repetition rate opening switches are essential for the development of high energy inductive storage and the eventual design of compact systems.
- Materials. Because the size, weight and cost of pulsed power systems are directly related to the energy-storage density of materials (dielectrics, magnetic materials, electrode properties, etc.) basic research is essential in this area.

- Prime Power. All pulsed power applications would benefit greatly from the development of prime power systems with low cost, increased power density and increased fuel efficiencies. Particular emphasis should be placed on systems which minimize power conditioning and intermediate storage requirements.

1.3 Sources

Both endo and exoatmospheric applications were considered by the workshop; however, the necessary expertise to consider critical needs in electron sources was not present. Additional evaluation of research needs for electron sources is required.

Significant improvements of sources will not result from refinements of present sources but rather from new approaches. Accompanying the introduction of novel approaches must be the development of diagnostic techniques. Issues include:

- Diagnostics for charged particle sources
- Theoretical understanding of negative ion formation
- Improved repetition rate for high intensity ion/electron sources
- Decreased energy spread of emitted beams and investigation of the origin of noise in sources
- Scalability of new source concepts
- Beam formation and extraction of high current ion/electron sources with emphasis on brightness.

1.4 Accelerators

Accelerators are required for the demonstration of key physics issues in propagation, target interaction and sensor observables, and for the eventual applications. Thus devices are required to cover a variety of parameter regimes. Furthermore, the parameter regimes are distinct for the endo and exoatmospheric applications. Neutral or neutralized beams of < 1 Ampere with extremely low emittance are required for the exoatmosphere. In contrast, the endoatmospheric application requires currents in excess

of 1 KA dependent upon whether the goal is the demonstration of propagation, injection into another accelerator, or a weapons systems.

For each situation (neutral or charged) there exist conventional approaches involving the extension of current technology with relatively low risk. For example, RF linacs are used for the exoatmospheric applications and various induction linac types are used for the endoatmospheric applications. For each there are novel approaches which promise payoff in, for example, size (gradient) and weight. Opportunities exist for basic theoretical and experimental research with all accelerator concepts. Many of these are device specific but some, especially beam dynamics in multistaged devices, are generic. It must be recognized, however, that considerable dollar investment is required to impact many experimental areas, especially for proof-of-principle demonstrations of new concepts. Exoatmosphere issues include:

- Emittance
- High gradient and low momentum spread
- Strong focusing elements
- Diagnostics for emittance during acceleration
- Improved higher order, beam dynamics - transport codes
- Theoretical analysis of new concepts and proof-of-principle experiments.

Endoatmosphere issues include:

- Develop new and alternative acceleration concepts
- Theoretical analysis (modeling and simulation) for transport in multistaged systems
- Pulse power, switching, rep rate and low inductance
- Materials for high flux swing magnets
- Dielectric breakdown; basic understanding of unipolar and bipolar pulses
- Theory and lab scale experiments for new concepts.

1.5 Propagation

Successful particle beam propagation in air is mandatory for viable endoatmospheric applications. Propagation requires creating a reduced density channel with early pulses of a multiple pulse train. Subsequent pulses must then follow the channel with minor attenuation. Topics appropriate for research are basic air thermochemistry and beam instabilities.

Information about exoatmospheric propagation of neutral beams is well in hand. Research opportunities do exist in examining the propagation of a charge-neutral plasma beam (plasmoid) over substantial distance outside of the atmosphere.

Endoatmospheric issues include:

- Determine recombination rates and cross sections for atoms, molecules and hydrated complexes.
- Determine effects of nonequilibrium vibrational and rotational populations on hydrodynamics
- Investigate the effects of "dirty air"
- Evaluate importance of relaxation and thermalization of excited states and secondary electrons
- Improve existing models of hose and two stream instabilities
- Determine importance of filamentation
- Develop economical computer simulation methods to investigate saturation mechanisms
- Perform low energy experiments with suitable diagnostics to validate models.

Exoatmospheric issues include:

- Evaluate plasmoid deflection in the earth's field
- Investigate growth of macro and microinstabilities in plasmoids
- Investigate self-pinched plasmoid configurations for extended propagation range.

1.6 Beam-Material Interactions

The purpose of a particle beam weapon (or, indeed, of any weapon) is to inflict damage on a target in such a manner as to disable or destroy it. The ultimate utility of a particle beam weapon depends upon how it interacts with targets. For this reason beam-material interaction studies must receive a reasonable degree of emphasis in any systematic balanced research program in weapons applications of particle beam technology.

Considerable effort has already been expended and the research area is somewhat mature; however, potentially high impact areas remain to be investigated. One area not usually included under this topic but of crucial importance is beam sensing both near the accelerator and near the target. Issues include:

- Nuclear radiation emitted from thick targets due to high energy ion bombardment
- Thermo-mechanical damage
- Collective effects in material interactions - multipulse preconditioning
- Low flux signatures and beam sensing signatures - what is the magnitude of the return signal?
- High flux signatures
- Energy deposition required to initiate chemically reactive materials
- Response of electronics and electronic components
- The behavior of high flux beams in layered targets
- Extremely high energy deposition initiated materials and structural response. Multipulse effects.

1.7 Concluding Remarks

For convenience in planning a research program, technical issues in various subareas of particle beam technology have been identified.

It is appropriate that particle beam technology should be pursued as a technological opportunity with a wide variety of potential applications. Certainly the bulk of that effort should be dedicated to the technology without reference to any specific military mission. Nevertheless it is important to perform at a much lower level, systems integration studies and military mission analyses to avoid pursuit of ideas solely for their scientific interest without regard to potential military value. Research for its own sake can be beneficial in serendipitous ways, of course, and should not be discouraged. But with limited resources, it is important that DoD funded research in particle beam weapons be guided by systems integration studies and military missison analyses. This point was evident in the overview statement by Dr. Tsipis of MIT.

One of our concerns before the meeting was whether meaningful issues appropriate for PBW research could be discussed in an unclassified context. The workshop participants, a substantial fraction of whom had been involved in the classified technology effort, were able to generate a compendium of unclassified research needs too extensive to be presented in this summary. They are described in the remainder of this report. We take this as evidence that access to the classified effort is not a requirement for the design of PBW related research (research being distinct from exploratory and advanced development). This is also significant in bringing together scientists who have not had prior contact with the classified effort in the PBW-related research programs. It was clear from the workshop that there is a need for the support of "new performers" who may have fresh approaches to some of the traditional limits to PBW technology.

It is not the purpose of this survey of research issues to indicate detailed priorities or plans. These will evolve from several data sources including this report. However, we were impressed with the appearance of the need for diagnostics within all of the five areas.

This summary was prepared entirely from the output of the workshop participants, the invited speakers, the panel chairmen, and the executive committee. To the extent that this summary is an accomplishment, it reflects their expertise and hard work. To the extent that it falls short, the authors, B. D. Guenther, R. Lontz, and J. L. May, accept the responsibility.

1.8 Speakers, Chairmen, and Executive Committee

Speakers

Particle Beam Research

Dr. George Gamota, Office of the Under Secretary of Defense for Research and Engineering

Particle Beam Weapons - A Technical Assessment

Dr John Parmentola, Massachusetts Institute of Technology

Beam Materials Interactions

Dr. Tony Armstrong, Science Applications, Inc.

Propagation

Dr. Edward Lee, Lawrence Livermore Laboratory

Accelerators

Dr. David Judd, Lawrence Berkeley Laboratory

Sources/Injectors

Dr. Steven Trujillo, IRT Corporation

Power Generation and Conditioning

Dr. Ian Smith, Ian Smith Associates

Panel Chairmen

Sources/Injectors

Dr. Thomas Hayward, Los Alamos Scientific Laboratory

Propagation

Dr. Edward Lee, Lawrence Livermore Laboratory

Accelerators

Dr. Donald Eccleshall, Army Ballistic Research Laboratory

Power

Dr. K. Kristianson, Texas Tech University

Beam Material Interactions

Dr. Thomas Roberts, Army Missile Command

Executive Committee

Dr. John Bayless, Defense Advanced Research Projects Agency

Major Harald Dogliani, Air Force Weapons Laboratory

Dr. Donald Eccleshall, Army Ballistic Research Laboratory

Dr. Bob Guenther, Army Research Office

Dr. Larry Havard, Ballistic Missile Defense/Advanced Technology Center

Captain Robert Hoberling, Foreign Technology Center

Dr. Charles Huddleston, Naval Surface Weapons Center

Dr. Robert Lontz, Army Research Office

LTC John May, Air Force Office of Scientific Research

Dr. Gerald Peters, Naval Surface Weapons Center

Dr. Thomas Roberts, Army Missile Command

Dr. David Straw, Air Force Weapons Laboratory

Dr. Ihor Vitkovitsky, Naval Research Laboratory

Administrative support provided by Air Force Reservists:

Captain Mike Strocio

Captain Brendan Godfrey

Major David Finkleman

II. PULSED POWER

2.1 Preface

The approach to identifying and prioritizing research and technology alternatives for developing pulsed power systems requires a critical examination of existing or technically feasible devices, components, and materials in relation to relevant phenomena, processes, properties, fabrication techniques, and operational criteria. The workshop on pulsed power - power conditioning systems, in attempting to do the above, divided their comments into the following areas:

(2.2) Prime Power
(2.3) Energy Storage
(2.4) Pulsed Shaping
(2.5) Switching
(2.6) Materials
(2.7) Components

Systems integration, diagnostics, and rf power sources were also considered but no views are reported on them for specific reasons. Systems integration, while important in the overall development of pulsed power, seemed inappropriate for study with basic research (6.1) funds. For rf power sources, no one was in attendance who was knowledgeable of the issues involved. Finally, while better diagnostics are almost always useful, it was not a subject which was easily addressed by this workshop in the time available.

Of the technical areas listed above three stood out as having higher priority than the others: switching, prime power, and materials. Major technology advances in these areas could dramatically affect the feasibility and practicability of various specific weapon concepts. Switching is of highest priority because utilization of the present technology of prime power and power conditioning is most often limited by it, especially for many endoatmospheric applications where weight and volume are not major

issues. Therefore, because of its priority, the central issues requiring broad, basic research are discussed in more detail for switching than for the other areas.

2.2 Prime Power Sources

Issues: Can high-energy pulsed power sources be developed that eliminate the need for many power-conditioning components (e.g., storage, switches, etc.)? Can pulsed power sources for PBW be developed that operate at high average power (10-1000MW)?

Priority: Very high. Innovative pulsed prime power techniques might bypass other difficult technologies of storage, switching, etc.

Research Needed: Conceptual design studies and laboratory experiments.

Options:

Energy Source	Short Pulse	Quasi-CW	Conversion Methodology
o Chemical	100GW	100MW	MHD; rotating pulsed machines
o Nuclear	100GW	100MW	Pulsed MHD, rotating pulsed machines
o Explosive	1TW	100MW	Flux compression; MHD
o Fuel cells, batteries	10MW	10MW	———

Significant Parameters

- Weight, volume, and fuel requirements (particularly for space applications) which tend to favor nuclear approaches.
- Cost, lifetime, maintainability, standby, and testing requirements for all systems.

2.3 Energy Storage

Issues: Can increased energy density be stored in repetitively-pulsed power generators with reduced losses and rapid energy transfer?

Priority: High. Significant improvements in energy density will provide the capability for large repetitively-pulsed loads. Significant improvements in inertial energy storage have recently been made. Further advances in inductive energy storage are limited by requirements for an opening switch.

Research Needed: Participation in such energy storage research by more than one organization, including:

- Demonstration of improved energy density from repetitively-pulsed devices with rapid energy transfer, and
- Research in materials with increased structural integrity.

Significant Parameters

- Energy density
- Repetition rate
- Peak and average current
- Peak and average power
- cost per Joule
- losses
- Peak voltage
- lifetime

Options:

Extension of current technology

- Capacitive storage
- Chemical storage (e.g., explosives, fast discharge batteries)

Promising

- Inductive storage (e.g., primary requirement for a repetitive opening switch, and research in the structural integrity of materials.)

2.3 Energy Storage (Cont.)

Most Promising

- Inertial storage - rotational and linear systems (e.g, further reduction in output pulsewidth and research in materials, for example: moving contacts, bearings, and epoxys for use at high velocities.)

Speculative

- Superconducting inductive storage (e.g., need higher transition temperature superconductors).

2.4 Pulse Shaping

2.4.1 Low Weight, Volume, Cost Pulse Shaping Circuits

Issues: Can the limitations of present Pulse Forming Lines (PFL) and Pulse Forming Networks (PFN) be alleviated, e.g.,

- o Low energy density, high weight and cost.
- o Fundamental limitations in:
  1) Field strength, and
  2) Material properties.

Priority: High. No work in this area is currently in progress.

Research Needed: Laboratory experiments.

Options:

Extension of current technology

- o reliable operation at high electric field stresses in present dielectrics

Promising

- o higher usable field strength at electrodes by using surface coating

Speculative

- o higher dielectric strength materials (e.g., no clear candidates)
- o lower loss dielectrics
- o weaker time dependence of breakdown strength

Significant Parameters

- o Electric Field Strength
- o Dielectric Constant
- o Energy Density

2.4 Pulse Shaping

2.4.2 Series Discharged Pulse Shaping Elements

Issues: Can reduction or avoidance of difficult repetitive switching requirements be achieved by the development of series discharged pulse shaping elements?

Priority: High. Development of techniques and pulse shaping elements could alleviate difficult switching requirements.

Research Needed: Modeling, trade-off studies, methodology, laboratory experiments.

Options: Use of multiple pulse forming line discharged in series to obtain a pulse train with interpulse spacing in the range of 10 ns to 100 ns.

Significant Parameters

- o Number of pulses in a pulse train
- o Acceptable pulse shape
- o Pulse shape variability
- o Pulse repetition rate

2.5 Switching

Issues: Switching is one of the major technology issues associated with the development of power sources for Particle Beam Systems. Power sources are required with average powers of 10^7 - 10^9 watts and peak powers of 10^7 - 10^{12} watts. Switches need to be developed which can withstand high voltages, high current densities, and pass large energies per pulse with high repetition rates, high reliability, and low weight and cost.

Priority: Very high.

Research Needed: Theoretical research and analysis, materials development, and laboratory switching experiments.

Options: The following are some of the generic types of switches that with further development may meet requirements:

- closing switches
  1) gas (solid, liquid, gas, vacuum)
  2) saturable reactors
  3) cross-field
  4) ignitrons
  5) thyratrons
  6) solid state
  7) mechanical
  8) surface flashover
- opening switches
  1) plasma (instabilities, cross-field, e-beam, fuses)
  2) superconducting
  3) mechanical
  4) solid state

Significant Parameters: Each of these switching options must be evaluated in terms of their present or postulated performance as determined by some or all of the following factors:

- phenomena/processes
  1) breakdown

PULSED POWER

2.5 Switching (Cont.)

- gas
- vacuum

2) flashover (surface)

- gas-solid interfaces
- vacuum-solid interfaces

3) electrode erosion

4) heat transfer

5) superconduction

6) flow dynamics

7) plasma chemistry

8) combustion processes

9) ionization and recombination processes and times

10) materials and materials properties

- basic (strength, friction, temperatures, etc.)
- bonding (techniques)
- composites
- dielectric (breakdown, permittivity)
- magnetic (higher permeability, higher saturation)
- solid state (for new thyristors)
- superconductors (higher transition temperatures)

o fabrication techniques

o operational criteria

1) reliability and fault analysis techniques

2) exoatmospheric operation - special conditions

3) endoatmospheric operation - special conditions

2.5 Switching (Cont.)

The switching options can be grouped by switching media which determine the relevant evaluation factors

- vacuum: thermionic devices, triggered vacuum gap

    1) breakdown mechanisms
    2) recovery/recombination
    3) plasma dynamics/gas discharte physics
    4) stability/jitter
    5) reliability/complexity/life
    6) channel formation/inductance
    7) analytic/computer models
    8) electrode erosion
    9) gas flow dynamics
    10) surface physics
    11) emission mechanisms
    12) e-beam energy recovery/perfeance

- low-pressure: thyratron, crossatron, ignitron, e-beam, cross-field interrupter

    1) breakdown mechanism
    2) recovery/recombination
    3) plasma dynamics/gas discharge physics
    4) stability/jitter
    5) reliability/complexity/life
    6) channel formation/inductance
    7) analytic/computer models
    8) electrode erosion
    9) gas flow dynamics
    10) surface physics
    11) emission mechanisms
    12) e-beam energy recovery/perfeance

- high-pressure: pressurized gaps, e-beams, circuit breakers

    1) breakdown mechanisms
    2) recovery/recombination
    3) plasma dynamics/gas discharge physics
    4) stability/jitter
    5) reliability/complexity/life
    6) channel formation/inductance

2.5 Switching (Cont.)

7) analytic/computer models
8) electrode erosion
9) gas flow dynamics
10) surface physics

o solid state: Light-activated silicon switch (LASS), silicon controlled rectifiers (SCR), Hall-effect devices

1) breakdown mechanisms
2) recovery/recombination
3) plasma dynamics/gas discharge physics
4) stability/jitter
5) reliability/complexity/life
6) channel formation/inductance
7) analytic/computer models

o state transition: saturable reactor, superconducting switches, fuses

1) breakdown mechanisms
2) recover/recombination
3) plasma dynamics/gas discharge physics
4) stability/jitter
5) reliability/complexity/life
6) channel formation/inductance
7) analytic/computer models
8) conductor-insulating transition/state transition

o surface: surface breakdown, high-pressure and vacuum

1) breakdown mechanisms
2) recovery/recombination
3) plasma dynamics/gas discharge physics
4) breakdown mechanisms
5) recovery/recombination
6) plasma dynamics/gas discharge physics
7) stability/jitter
8) reliability/complexity/life
9) channel formation/inductance
10) analytic/computer models
11) electrode erosion
12) gas flow dynamics
13) gas decomposition/chemistry
14) surface physics
15) emission mechanisms

PULSED POWER

2.6 Materials

2.6.1 Materials for Prime Power and Storage

Issues: The need for transportable systems in many applications dictates equipment with high power density and high efficiency optimized for utilization in both pulse and intermittent duty cycles. Can advanced materials be developed which will enable this to be done?

Priority: Medium.

Research Needed: Theory, materials development and laboratory experiments on:

- o Magnetic Materials - High permeability, saturableflux density, low loss, good mechanical strength.
- o Conductive Materials - Improved mechanical strength to prevent flow under stress.
- o Superconductors - Higher transition temperatures, current density, field strength.
- o Dielectrics - Higher dielectric constant breakdown strength, lower dissipation factor.
- o Composites - Improved tensile strength, and bonding materials and techniques; cycling of mechanical loads.

Options:

- o Dielectrics - Evaluate available materials and extension of technology to improve dielectric constant with due consideration of dielectric strength.
- o Composites - Extension of ongoing efforts to increase mechanical strength (fibers, Kevlar, etc.).
- o Magnetic Materials - Extension of ongoing work (amorphous metals).
- o Conducting Materials - Extension of current technology to improve mechanical strength.
- o Superconductors - Evaluate ongoing efforts to increase transition temperatures.

2.6 Materials

2.6.2 Materials for Capacitive Storage and Power Transmission

Issues: Capacitive storage for both DC and pulsed charging is widely used in present systems. Even if inductive storage is more fully developed, dielectrics for insulation and power transmission are critical. Materials with higher usable field strengths, energy densities, and lower losses are required.

Priority: High.

Research Needed: Theory and experiments to develop better materials and to determine how to utilize the intrinsic dielectric strength of dielectrics in bulk samples.

Significant Parameters:

- Film materials for conventional capacitors
- High-dielectric-constant, high-resistivity liquid for
  1) bulk dielectrics, and
  2) impregnents for capacitors.
- Materials for producing bulk dielectric with strength approaching the intrinsic strength of the material.

2.6 Materials

2.6.3 Materials for Switching and Power Conditioning

Issues: Surface breakdown physics as related to materials, and surface erosion of electrodes and materials caused by UV and electrons on dielectrics needs to be understood so that their limitations might be mitigated. Also needed are magnetic materials with higher μ and $\beta_{saturation}$ for switch applications.

Priority: High. Payoff may be particularly important in size and weight reduction and even required for reliability.

Research Needed: Theoretical studies and analysis, and laboratory experiments on:

- o Ceramics and plastics -- new materials, better understanding of surface physics
- o Metals -- evaluation of existing alloys, surface preparation and better understanding of erosion rates under CW and pulsed high current densities and large charge transfers, and new magnetic materials.

Also additional cooperative research is needed between materials and pulsed power groups.

Significant Parameters:

1) Ceramics - high voltage hold-off
2) Dielectrics - hold-off recovery after breakdown
3) Metals - low erosion rates, higher μ and $\beta_{saturation}$
4) Degradation of materials in a contaminated environment

2.7 Components

2.7.1 Transformers

Issues: Scalability to very high energies and to high repetition rates needs to be established (transformers represent low-cost alternatives to voltage-multiplying circuitry).

Priority: High.

Research Needed: Primarily laboratory experiments.

Significant Parameters:

- o Scalability to higher currents, voltages, energies
- o Repetition rates
- o Energy losses
- o Evolution of gases in insulating oils under stress

2.7 Components

2.7.2 Solid Dielectric

Issues: The development of high reliability capacitors with performance specification requirements which may in some cases be mutually exclusive and therefore require special development and trade-off studies for specific applications. Desired characteristics include:

- o High energy density (> 750 Joules/lb)
- o Low cost (<< $1/Joule)
- o Long life (> 10^8 discharges)
- o Low loss (D < 10^3)
- o High repetition rate

Priority: Very high - exoatmospheric operation; medium - endoatmospheric operation.

Research Needed: Basic studies, mainly experimental, on insulating films and impregnants.

Significant Parameters:

- o Weight
- o Volume
- o Cost
- o Reliability

Options:

- o Foil and insulating films
- o Ceramic
- o Electrolytic

2.7 Components

2.7.2 Dielectrics

2.7.2.2 Water/Liquid Dielectric

Issues: Can the time-before-breakdown versus voltage be extended for water and other liquid dielectrics.

Priority: High

Research Needed: Laboratory experiments.

Options:

- o Electrode surface preparation
- o High pressurization (up to 100 atmospheres)

Significant Parameters:

- o Long $\tau_{effective}$ desired (> microseconds)
- o Low area dependency

2.7 Components

2.7.3 Cables and Connectors

Issues: The trend is toward higher-voltage interconnects between subsystem elements. Can cable technology be improved to keep pace with this trend?

Priority: Medium.

Research Needed: Design and laboratory experiments on:

- o Breakdown and flashover strengths
- o Handling of high voltage under repetitive pulsing at high rates.

Options:

- o Solid, liquid, gaseous insulators;
- o Graded insulators;
- o Improved geometries.

III. SOURCES

3.1 Preface

The workshop dealing with issues in sources divided their comments into three major areas:

(3.2) Electron Sources (endoatmospheric)

(3.3) High Intensity Ion Sources (exoatmospheric)

(3.4) High Quality Ion Sources (exoatmospheric)

Sources exist for each major beam type considered for beam weapons. Electron sources, high intensity (KA) ion sources, and a number of negative ion sources, suitable for high quality ion beam generation, have been developed sufficiently to allow testing of advanced beam accelerator concepts. However, significant development will be needed, including the invention of novel new concepts, before sources adequate for fully developed beam weapon accelerators can be produced. The workshop group did not include experts on electron sources and thus, that subject received only slight treatment. Positive ion sources for intense (KA) beams exist but were also given only general treatment because major problems did not seem to exist. High quality ion sources received the bulk of attention because the negative ion sources needed for weapons-grade accelerators do not yet exist, and a research program that will result in their development is not yet clearly defined.

In general, (1) there appear to be several promising approaches to achieve suggested parameters for negative ion sources; (2) detailed modeling, particularly in the plasma and interface region of sources, is in need of work, and (3) improved diagnostics need to be developed.

3.2 Electron Sources

Issue: Can improvements be made in the pulse shapes and current distributions of intense relativistic electron beams?

Research Needed: Development of new cathode concepts such as:

- o Laser activated cathodes.

SOURCES

3.3 High Intensity Ion Sources

Issue: What developments could provide further advancement in intense ion sources?

Research Needed: Further developments would be aided by:

- Improved diagnostics (difficult because of the need for being close to the beam path).
- Better definition of needed parameters.
- Repetitive pulsing of the anode (renewable liquid foil anodes are a possible choice).

3.4 High Quality Ion Sources

3.4.1 Status of Sources

Issue: What areas of improvement are there for high quality ion sources?

Options: The present approaches to ion sources are well developed and factors of two are all that are likely to result from further development. The most advancement will come from new approaches, such as:

- o Negative ion sources.
  - Laser induced emission
  - Emission via heavy ion bombardment.
- o Electrically neutralized sources.

3.4 High Quality Ion Sources

3.4.2 *Negative Ion Sources*

Issue: What improvements can lead to better negative ion sources?

Research Needed: Modeling of negative ion sources can lead to improvements. A theoretical/computer-simulation model of the plasma chemistry, surface-plasma boundaries, and extraction dynamics should be developed in order to gain a better understanding of the so-called "direct extraction, surface-plasma" sources. The goal of this research should be a theoretical model (probably including a simulation program) which can be used as a tool for developing design improvements for such sources (e.g., Dudnikov source) and to establish the fundamental scaling relationships for increasing beam current without degrading emittance (or reducing it).

Options: A plasma chemistry computer model of the basic volume processes can be developed along the lines of the plasma chemistry codes now used in modeling gas-laser plasmas. Separate models and basic research in the theory of plasma-surface boundaries probably require a different approach, as does extraction dynamics modeling (which could possibly rely on existing particle dynamics codes). However, a unified study of the interrelation between these areas will eventually be required, most likely starting with a plasma-chemistry model as the core element.

Significant Parameters: Ability to predict scaling into high current, high brightness regimes.

Unique Capabilities: The potential to remove the "sourcery" out of the art of "ion sourcery."

IV. ACCELERATORS

4.1 Preface:: The working group reviewing accelerator technology research issues for PBW attracted about 28 participants from as many institutions. In spite of this large attendance, however, some areas of the accelerator community were still not adequately represented. Within the time constraint of this meeting, this group attempted to identify those generic issues where better fundamental understanding is required to advance the state-of-the-art of accelerators, and to identify accelerator concepts potentially promising for PBW.

The following pages give a brief discussion of PBW requirements, and generic issues associated with accelerator technology. These are then followed by a specification sheet for each accelerator concept discussed. By necessity, each specification sheet is very brief, pointing only to major issues and parameters of interest. No research priorities are mentioned among the various accelerator concepts, however, an attempt was made to achieve some normalization and differentiate between existing technology, on the one hand, and new, speculative ideas on the other. It must be pointed out that many of the judgements, and performance estimates, are very subjective, often based on theory alone. Further, the list of issues and accelerator concepts discussed, while long, is not exhaustive. Some important subjects, engineering feasibility, for example, were not mentioned and others, such as beam diagnostics, were addressed only slightly.

4.2 Overview

4.2.1 Endo vs Exo: In view of the unclassified nature of the Workshop, the significant accelerator parameter requirements were left purposely vague. This constraint gave some difficulty because many research issues on accelerators are device specific. However, to give some guidelines to the participants, a set of general accelerator beam parameters were outlined. These parameters are qualitative, but they do show the direction of research needed.

For endoatmospheric application, the need is for very compact accelerator systems, and very high current (multi kiloampere) beams. The preferred particles are electrons delivered in short pulses at a high repetition rate. The accelerator energy required will be several hundred MeV's and the energy delivered at the target will be megajoules with peak powers of terawatts.

The desired accelerator beam characteristics are poorly defined; these parameters are strongly dependent upon beam propagation in the atmosphere. Beam emittance *per se* is not the fundamental criteria. However, beam angular divergence and momentum spread are important. For endoatmospheric application, beam divergence should be of the order of 10^{-3} radians and momentum spread $<0.1\%$.

For exoatmospheric application, the need is also for very light and compact accelerator systems. The other parameters are, however, rather different. The requirement is for acceleration of ion beams. Propagation in space requires the accelerated beam to be space-charge neutralized.

4.2.2 Generic Issues: Despite the extremely wide variety in accelerator concepts proposed for PBW application, a number of basic problems are common to all. Although each one of these problems will have its own twist depending on the accelerator concept it is applied to, basic research opportunities exist in addressing the underlying fundamentals of these problems. A full discussion of these issues is not the intent here, but the following comments are in order.

4.2.2.1 Current Limits in Conventional Accelerators and Beam Transport Systems: Upper limits for the beam current and significant emittance growth are observed in existing rf linacs when the particle intensity is increased. Recent theoretical studies on beam transport in conventional accelerators have identified instabilities associated with pertubations in the electrostatic self-field of the particle beams as a cause for these effects. They appear to pose a fundamental intensity limit for systems in which the beam is accelerated and/or focused over a distance

that is large compared with one particle oscillation period in the transverse focusing fields. This issue is of direct relevance to particle beam systems that use rf linacs and may be relevant to indution linacs and other concepts.

Other issues include space charge effects, microinstabilities, neutralization effects, and pulse shaping. Also, there are the special beam transport problems encountered at injection and in staging accelerators, namely, that of matching beam emittances of one accelerator type or section to the acceptance of the next accelerator stage.

Fundamental understanding of beam transport phenomena and their associated limitations are a prerequisite to achieving the high current levels desired and thus should have a very high priority in particle beam research.

4.2.2.2 Beam Diagnostics: Beam diagnostics and control are other issues common to all accelerator concepts. Needed are nondestructive, real-time measurements of beam emittance, beam divergence in real space, and momentum spread for neutral and neutralized beams. While some techniques currently exist, many new approaches will be required for PBW.

4.2.2.3 Other Generic Issues: The following is a list of other research subjects mentioned during the Workshop:

a. Beam transport and neutralization effects in low pressure gas.
b. Theoretical studies of electron trapping and cleaning effects as related to focusing, emittance growth, etc.
c. Studies of neutralization effects and techniques for transport of the beam between accelerator gaps, including focusing.
d. Experimental studies of space charge related instabilities to understand and develop means of suppressing these instabilities.

4.2.3 Accelerators: A major output of this working group was to identify accelerator concepts potentially capable of meeting the requirement for PBW. The accelerator field is extremely varied especially when taking into account all the untried concepts. The field ranges from

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"conventional" accelerators, with long history of successful development and operation, to newer concepts still requiring proof-of-principle. The use of conventional accelerators for PBW applications will require extension of the state-of-the-art beyond existing technology. On the other hand, some of the newer accelerator ideas, although conceptually promising for this application, have much further to go in the development cycle before even proof-of-principle can be demonstrated.

An appreciation for the breadth of the spectrum of potential concepts was given by Dr. D. Judd, UC, Berkeley, the invited speaker on the subject. Table 4.1 lists various accelerator concepts, and some o the laboratories involved in developing these concepts.

Following Table 4.1 are specification sheets for each subject and each accelerator concept giving a brief description of: issues or potential, status, research needed, and significant parameters.

TABLE 4.1
CLASSIFICATION OF ACCELERATOR SYSTEMS

Systems	Related Projects
I. Noncollective ("conventional") Accelerators	
1. Radio-frequency linac (ions)	LASL AT-2
2. Induction linac (electrons)	NBS; LLL-ATA, Sandia RADLAC, LBL-Betatron
II. Collective Accelerators	
1. Collective E_R Focuses Ions Electrons (supplied or naturally present) tend to neutralize radially defocusing self-field of intense ion beam.	Sandia - High Current Ion Linac UC Irvine - Toridial Accelerator
2. Collective E_Z Accelerates Ions	
a. Moving well, virtual cathode	EG&G Luce Diode; Boeing Aerospace Luce Diode; Sandia Ionization Front Accelerator (with laser light). UC Irving Ionization Front in gas gradient; Physics International Ionization Front; North Carolina Dielectric Guide; Spire Corp. Dielectric Guide; U. of Maryland Dielectric Guide
b. Moving wave train on an electron beam	
i) Cyclotron waves Speed controlled by external B field over wide range	Austin Research Autoresonant Accelerator
ii) Space charge waves (Doppler shifted plasma osc). Speed controlled by geometry (pipe radius/beam radius). Difficult for $\beta < \sim 0.2$	NRL Converging Guide; Cornell
III. Hybrids (e.g., Autoaccelerator) Precursor beam replaces external supply to energize induction linac accelerator modules.	NRL Autoaccelerator.

4.3 Radio-Frequency Linacs

Potential: Conventional, well-developed proton accelerator. Current limited, gradient limited, capable CW operation, high energy, low divergence, power/weight ratio poor.

Status: Radio-frequency linacs operational for physics research. State-of-the-art inadequate for PBW; requires substantial extension of technology.

Research Needed: Injection and preservation of bright beams, strong focusing, minimization of beam emittance and momentum spread, beam diagnostics, accelerating gradient, power/weight ratio. Radio-frequency voltage breakdown phenomena, quadrupole magnet materials (see next page), power sources, higher order beam dynamic studies to deal with higher currents, space-charge phenomena, instabilities.

Options:

- Choice of accelerating structures
- Multi-beam acceleration.

Significant Parameters

- Current
- Energy
- Beam Emittance
- Divergence
- Power/weight ratio
- Efficiency
- Reliability

4.3 Radio-Frequency Linacs (Cont.)

Research Needed on Permanent Magnet Material for Accelerator Applications:

The transport of intense-charged particle beams requires strong focusing forces to overcome the space charge forces in the beam. The problem is most critical in the low energy portion of linear accelerators where the space charge forces are highest and there is little space available for the magnetic quadrupole lenses. The development of rare earth cobalt permanent magnet material has made it possible to produce small quadrupoles that are two to three times stronger than the best electromagnets, however, even stronger magnets are needed.

The properties of permanent magnet material in the second and third quadrants of the B, H curve can be specified by three quantities: the B intercept or remanent field B_r, the H intercept or coercive force, H_c, and the "squareness factor", H_k, which is a measure of the point at which the curve becomes nonlinear. H_k is the value of H for which $B-H = 0.9\ B_r$.

The design of a strong quadrupole requires that the B, H curve be nearly linear over a wide range. The maximum pole tip field achievable depends on B_r however, there are portions of the magnet where the material is driven into the third quadrant by an amount equal to the pole tip so that the practical limit is determined by the point in the third quadrant at which the material becomes nonlinear, i.e., H_k. Unfortunately, in presently available materials, large B_r values seem to have small H_k values. Some typical values for material manufactured by Hitachi are:

Material	B_r (kG)	H_c (kOe)	H_k (kOe)
Hicorex 90A	8.2	-7.5	-10
Hicorex 90B	8.7	-8.2	-13.2
Hicorex 96A	10.25	-9.5	-9.6

4.3 Radio-Frequency Linacs (Cont.)

Although 96A has a very large B_r, it is unusable for quadrupoles because of the small H_k. There has been little commercial interest in controlling material properties in the third quadrant as most applications do not drive the material into this region. Very little information is available from material manufacturers on control of these properties due to the lack of instrumentation and research capability, and the proprietary nature of such information. Research on the improvement of these materials, perhaps by investigating various alloys and also understanding what factors (temperatures, cooling rates, etc.) in the manufacturing process affect these qualities, would be of great value for the production of more intense particle beams.

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4.4 Induction Linacs-Pulse Line

Potential: Induction-type linac accelerates electrons, potentially capable very high currents (~ 100 kA), pulse length (~ 10 ns), gradient up to 10 MV/m, good power/weight ratio, beam quality limited.

Status: Pulse-line linac has been under development for some time; requires extension of technology.

Research Needed:

- Experimental program for multi-section device
- Beam dynamic study dealing with instabilities
- Space charge
- Beam loss phenomena
- Repetition rate
- High-duty factor injection systems
- Switch synchronization
- Inductance effects
- Reliability
- Dielectric breakdown
- Pulse conditioning

Options:

- Blumlein
- Symmetric and assymmetric line pairs
- Three-line systems
- Recirculating
- Externally-switched configuration

Significant Parameters:

- Beam divergence and momentum spread
- Repetition rate
- Current
- Energy
- Power/weight ratio
- Efficiency
- Reliability

ACCELERATORS

4.5 Induction Linacs-Magnetic

Potential: Induction-type linacs can accelerate electrons or ions, demonstrated capability of high currents (~10 kA electrons) to high energy, pulse lengths ns to μs. Gradient limited, power/weight ratio good for short-pulse devices.

Status: Magnetic induction linacs are well understood. Operate with electrons, being developed for heavy ion inertial fusion. Require extension of technology for PBW and better understanding of beam transport phenomena.

Research Needed:

- Theoretical studies of high current beam transport phenomena
- Micro- and macro-instabilities
- Improved magnetic materials for long-pulse operation
- Energy storage and switching
- Techniques for radical improvement of power/weight ratio
- Power sources
- Switching

Options:

- Beam recirculation (microtron).
- Wide-interval pulse spacing vs continuous-pulse train
- Electron-proton

Significant Parameters:

- Beam divergence and momentum spread
- Current
- Efficiency
- Repetition rate
- Energy
- Power/weight ratio

4.6 Electron-Ring Accelerator

Potential: Could accelerate ions to high energy, current (kA) pulse length (ns), very high gradient up to 100 MV/m theoretically possible, good power/weight ratio, repetition rate, beam characteristics unknown.

Status: Of the collective ion accelerators, has had the most research done at several laboratories, proof-of-principle demonstrated in USSR, outcome speculative, beam characteristics unknown.

Research Needed:

- Demonstration of proof-of-principle in range of interest
- Control of electron ring formation and compression
- Theoretical simulation of beam dynamics
- Micro- and macro-instabilities

Significant Parameters

- Current
- Energy
- Beam divergence and momentum spread
- Pulse length and repetition rate
- Power/weight ratio
- Efficiency
- Reliability

4.7 Space-Charge-Wave Accelerator

Potential: Could accelerate protons, high current (>10 kA), pulse length (μs), possible staging for high energy, good power/weight ratio, gradients of up to 100 MV/m theoretically possible, repetition rate a problem, injection a problem, beam characteristics unknown.

Status: Research on this accelerator type is being pursued at several laboratories, outcome speculative, beam characteristics unknown, no demonstrated proof-of-principle.

Research Needed: Demonstration of proof-of-principle, control of wave-phase velocity at low β, injection systems, theoretical simulation of beam dynamics, instabilities, beam loading and nonlinear effects, etc., injection system

Significant Parameters:

- Current
- Power/weight ratio
- Efficiency
- Beam divergence and momentum spread
- Pulse length and repetition rate
- Reliability

4.8 Cyclotron-Wave Accelerator

Potential: Could accelerate ions, high currents (> kA), pulse length (μs), good power/weight ratio, high repetition rate conceptually possible, gradients of up to 100 MV/m, theoretically possible, staging a problem, beam characteristics unknown.

Status: Research on this accelerator type pursued at several laboratories, extensive simulation has been carried out, outcome speculative, no demonstrated proof-of-principle, beam characteristics unknown.

Research Needed: Demonstration of proof-of-principle, electro-dynamics studies required of wave formation, unwanted modes, wave amplitude and propagation control, etc. Theoretical studies of beam transport dynamics, instabilities, beam loading, nonlinear effects, etc., injection system.

Significant Parameters:

- Current
- Energy
- Beam divergence and momentum spread
- Power to weight ratio
- Pulse length and repetition rate
- Efficiency
- Reliability

4.9 Auto-Accelerator

Potential: Could accelerate electrons, current ($\sim$10 kA), pulse length (ns), high gradient ($\sim$10 MV/w), good power/weight ratio, high energy possible, repetition rate a problem, beam characteristics unknown.

Status: Research pursued for several years, small-scale proof-of-principle demonstrated, scalability to parameter range of interest not demonstrated, beam characteristics unknown.

Research Needed: Experimental program for multicavity device, large-scale proof-of-principle demonstration, theoretical simulation of beam dynamics, beam loading, instabilities and nonlinear effects, cavity coupling, injection system, low γ beam propagation.

Significant Parameters:

- Current
- Beam divergence and momentum spread
- Pulse length and repetition rate
- Reliability
- Energy
- Power/weight ratio
- Efficiency

4.10 Collective Focusing Ion Accelerators

Potential: Could accelerate electrons or ions, currents (<kA), pulse length (<μs), extraction a problem, beam characteristics unknown.

Status: Research on this accelerator type in its infancy, outcome speculative, no demonstration of proof-of-principle, beam characteristics unknown.

Research Needed: This accelerator is at the conceptual stage, research needed in all areas.

Options: Magnetically insulated ion diodes, Gabor lenses, magnetic mirrors, bumpy torus.

Significant Parameters:

- Current
- Energy
- Beam divergence and momentum spread
- Power/weight ratio
- Pulse length and repetition rate
- Efficiency
- Reliability

4.11 Collective Accelerators With Localized Ion Source

Potential: Could accelerate ions, high currents (up to 10 kA), pulse length (5 to 100 ns), very high gradient ($\sim$100 MV/m), good power/weight ratio, beam characteristics unknown, energy spread a problem, high energy and staging a problem.

Status: Localized ion source accelerators have achieved proton energies of 40 MeV, and Kr 400 MeV. Proof-of-principle in parameter range of interest not demonstrated, beam characteristics unknown, outcome speculative.

Research Needed: Theoretical studies and simulation for understanding underlying physics, beam formation, instabilities, scaling laws, etc. Proof-of-principle experiments, beam diagnostic and measurement techniques, power source, energy storage, E-beam generator.

Options: Luce Diode (ions produced from dielectric insert). Localized gas clouds, laser-produced ions, staging with slow-wave structure, use of modular electron beam generators.

Significant Parameters:

- Current
- Energy
- Beam divergence and momentum spread
- Power/weight ratio
- Pulse length and repetition rate
- Efficiency
- Reliability

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4.12 Ionization Front Accelerator

Potential: Could accelerate ions to high energy, high current (>10 kA), pulse length (ns), very high gradients of up to >100 MV/m theoretically possible, good power/weight ratio, beam characteristics unknown, repetition rate a problem, staging a problem.

Status: A small-scale device has been demonstrated. Proof-of-principle in parameter range of interest not demonstrated. Beam characteristics unknown, outcome speculative.

Research Needed: Theoretical studies and simulation to understand beam transport phenomena, large-scale proof-of-principle experiments, beam diagnostics, and measurement techniques. Power source, energy storage and switching.

Significant Parameters:

- Current
- Energy
- Beam divergence and momentum spread
- Power/weight ratio
- Pulse length and repetition rate
- Efficiency
- Reliability

4.13 Collective Particle Accelerator

Potential: Could accelerate electrons or ions, currents ($\sim$kA), pulse length ($\sim$ns), very high gradients ($\sim$100 MV/m) theoretically possible, good power/weight ratio, high energy possible, repetition rate a problem. Beam characteristics unknown.

Status: New concept, no demonstrated proof-of-principle, beam characteristics unknown, outcome speculative.

Research Needed: This accelerator is at the conceptual stage, research needed in all areas.

Significant Parameters:

- Current
- Energy
- Beam divergence and energy spread
- Power/weight ratio
- Pulse length and repetition rate
- Efficiency
- Reliability

4.14 Hadron Plasmoid Accelerator

Description: A new accelerator is suggested to provide 5 to 10 MA instantaneous (20 ns) pulses at several hundreds of MeV protons with small divergence (20 to 30 μrad), for producing a plasmoid beam with co-moving electrons. An intense high-energy plasmoid beam has several operational advantages in exoatmospheric military application. The Hadron plasmoid accelerator system is made up of the following key components:

- A large area, pulsed cold intense plasma ion source to produce $T_i \sim 0.50$ eV, 1 to 2 A/cm^2 light ions for 1 to 2 μs;
- A multi-aperture, multi-grid standing column injector to accelerate to 5 to 10 MeV and produce 10 to 20 A/cm^2 ion beam for 100 ns, to be injected in a multi-stage accelerator;
- A pulsed, multi-aperture drift-tube linac system, in which 100 to 200 A/cm^2 beam currents are stacked radially, the beams are neutralized and magnetically stabilized in drift tubes, electrostatic focusing at acceleration gaps by curved virtual electrode shaping produced by radial magnetic insulation (10 to 15 kG) pulsed fields; and
- Production of co-moving electrons for a 20-ns-intense hadron plasmoid beam.

Status: New concept, no history; speculative

Issues:

- Generation of pulsed cold intense plasma ion source.
- Low emittance, large current ion extraction, acceleration, bunching and focusing control for an injector.
- Multi-state, pulsed drift-tube acceleration, controlled focusing and emittance, current radial stacking.

4.14 Hadron Plasmoid Accelerator (Cont.)

- o High voltage stressing at magnetically insulated gaps, 50 to 100 ns, 2 to 4 MV/cm.
- o Development of pulse-power technology with controllable wave-form generation, inductive energy storage, opening switches, solid dielectric pulse times for 10 to 100 Hz repetition rates. Weight optimization.
- o Intense plasmoid beam propagation and confinement methods.

Research Needed: Laboratory-scale proof-of-principle experiments and simulational theoretical analyses.

Options:

- o A multi-aperture, electrostatic quadrupole focused linac structure with rf acceleration may replace the pulsed-drift-tube linac.
- o Beam aperture need to be adiabatically increased to provide beam colling.
- o Typically, 25 to 50 A currents can be accelerated to produce 1 μrad divergent beam to be launched by co-moving electrons.

Significant Parameters: 100 to 200 A/cm^2, 5 to 10 MA, 20 ns, 200 to 400 MeV, 20 to 30 μrad, hadron plasmoid. Option: 25 to 50 A, 1 ms, 200 to 400 MeV, 1 μrad plasmoid.

V. PROPAGATION

5.1 Preface

The subject of propagation was addressed at the meeting and reported here under the general categories:

(5.2) Air Chemistry

(5.3) Instabilities

for endo-atmospheric (CPBW) concepts and under the category

(5.4) Plasmoid Propagation

for exo-atmospheric pulsed energy beam concepts.

Successful endo-atmospheric propagation is mandatory for viable CPBW systems and requires the use of a multiple pulse train whose initial pulses must prepare a stable channel of appropriate geometric shape, mass density, high electrical conductivity and perhaps other electrodynamic characteristics, known and unknown. Successive charged particle beam pulses in the pulse train are then required to propagate along this prepared channel in a stable fashion with minimal power density attenuation. To support on-going studies of endo-atmospheric propagation physics, the following technical issues were presented to be relevant to the problem:

Air Chemistry Issues

1: Additional atomic data is required to support analytical predictions of the electrical conductivity of the electron-beam-driven air channel.

2: Determination of atomic, molecular and hydrated-complex recombination rates and cross sections.

3: Determination of the effects of non-equilibrium vibrational and rotational populations upon e-beam-driven channel growth.

4: Investigations of the effects of particulate and aerosol impurities (dirty air) upon the single and multiple pulses.

5.1 Preface (Cont.)

5: Determination of the importance of relaxation and thermalization of excited states and secondary electrons (energy below ionization potential) upon subsequent pulses in the pulse train.

Instability Issues

1: Improve existing models of hose and two-stream instabilities.

2: Determine the possible importance of filamentation and "other" less investigated instabilities.

3: Develop economical computer simulation methods for the investigation of non-linear instability behavior.

4: Study instability saturation mechanisms.

5: Perform low energy experiments to partially validate models and simulations. Develop appropriate diagnostics.

Plasmoid Issues

In the case of exo-atmospheric concepts, additional experimental and theoretical physics research is required on the propagation of charge-neutral-plasma-beams, namely "plasmoids," over substantial distances in the earth's magnetic field. Some of the more relevant issues are contained in the following questions:

1: Is the plasmoid beam significantly deflected by the earth's magnetic field?

2: Does the plasmoid beam expand during propagation to energy density levels which are too low to be useful?

3: Is the propagating plasmoid "beam" quality seriously degraded by macroscopic instabilities?

4: Can outward radial growth of the plasmoid "beam" be inhibited by "self-pinch" forces?

The following material characterizes the specific technical issues which were reviewed under the categories (5.2) - (5.4).

5.2 Air Chemistry

5.2.1 Real-Time Air Conductivity

Issues: To improve the atomic data base in available codes used to describe the real-time electrical conductivity σ in the electron beam driven air-channel.

Priority: High. The predicted pulse length of the electron beam which can stably propagate in the air-channel depends critically on σ and available codes containing σ-related uncertainties of a factor of 2.

Research Needed: Additional data is required on the following processes, listed in the order of expected importance:

- Recombination cross sections (electron and ion)

  1) $O_2^+ \cdot H_2O$
  2) O_4^+
  3) $O_2^+ \cdot N_2$
  4) N_3^+

- Ion-neutral reactions rates (cluster formation)

  1) Temperature dependence
  2) Density Dependence (saturation point)

     i) $O_2^+ + H_2O + M \rightleftharpoons O_2^+ \cdot H_2O + M$

     ii) $O_2^+ + O_2 + M \rightleftharpoons O_4^+ + M$

5.2 Air Chemistry

5.2.1 Real Time Air Conductivity, σ (cont.)

iii) $O_2^+ + N_2 + M \rightleftharpoons O_2^+ \cdot N_2 + M$

iv) $H_3O^+ + H_2O + M \rightleftharpoons H_3O^+ \cdot H_2O + M$

v) $N^+ + N_2 + M \rightleftharpoons N_3^+ + M$

vi) $N_2^+ + N_2 + M \rightleftharpoons N_4^+ + M$

Options:

- o Measurement of individual ion-molecule and electron cross sections and rate coefficients. (Some technique development is required).
- o Measurements of groups of relevant processes using partial simulation or global experiments, e.g., e-beam sustained discharges at intermediate power densities.
- o Measurement of individual electron-ion recombination coefficients.

Significant Parameters:

Cross sections and rates (temperature dependence and electron energy dependence).

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5.2 Air Chemistry

5.2.2 Recombination Rates and Cross Sections

Issues: What is the role of long term "chemistry" on propagation of charged particle beams in the atmosphere?

Priority: To be determined by phenomenology studies. Priority will be high if conductivity and molecular energy relaxation, at atmospheric pressure on the micro-second scale, are important.

Research Needed:

- o Phenomenology estimates.
- o Laboratory determination of electron dissociation cross sections.
- o Assessment and possible measurement of relevant chemical reaction rates.

Options:

- o Measurements of individual reaction rates or cross sections.
- o Measurements of conductivity and/or gas dynamics effects in "partial simulation" experiments.

Significant Parameters:

- o Gas pressures up to atmospheric.
- o Time scales of the order of microseconds.

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5.2 Air Chemistry

5.2.3 Impurity Effects

5.2.3.1 Particulate Impurities

Issues: What are the effects of particulate impurities on air chemistry? This involves inhomogeneous and heterogeneous reaction rate situations (ablation, ionization, etc.) which are not simply incorporated into calculational codes. Natural aerosols as well as deliberate counter measures (smoke, dust, etc.) can be anticipated as part of the particle beam environment.

Priority: Medium. Impurities can significantly impact propagation through

- o inhomogenities
- o conductivity modification

Research Needed:

- o Small-scale experiments to confirm the basic phenomenology and levels of effects for various solid particulates and aerosols in a high temperature propagation environment.
- o Theoretical analysis to assess potential effects and to correlate experimental data.

Options: Modify existing aerosol physics/high temperature laboratory facilities to the needs of beam propagation problems.

Significant Parameters:

- o Degree of inhomogenity
- o Particulate distribution parameters
- o Ablation rates
- o Conductivity

5.2 Air Chemistry

5.2.3 Particulate Impurities

5.2.3.2 Molecular Impurities

Issue: What are the effects of molecular impurities on air chemistry?

Priority: Not stated

Research Needed:

- Assessment of possible impurities and their concentration in the air.
- Assessment of kinetic processes that can occur involving these species and their products.
- Assessment of cross section/rate constant information for these processes.
- Ranking in order of probable importance.
- Small scale experiments to globally assess the effects of selected impurities.

Options:

- Literature search, analysis and calculations
- Small scale experiments

Significant Parameters:

- Effect of conductivity
- Effect of energy relaxation

5.2 Air Chemistry

5.2.4 Air Radiation As A Conductivity Diagnostic

Issue: There is a need to develop diagnostic techniques to resolve spatially and temporally the conductivity generated in air by a charged particle beam. Present interpretation of the experimental data is frequently limited by uncertainties in excited state reaction rates at elevated temperatures.

Priority: High

Research Needed: Laboratory scale experiments on air radiation generated by particle beams for varying beam and air conditions, and theoretical estimates of excited state reaction rates. Examples include:

- Diagnostic techniques for measuring electron concentration and "temperature" with nanosecond resolution.
- Chemiluminescence rates at various gas temperatures

  ($T_g \approx$ 2000 - 3000°K) such as:

  $$N = N(^2D) + M \longrightarrow N_2\ (C^3\ {}_{v\,=\,1}) + M \longrightarrow \lambda = 3371\ \text{Å}$$

- Collisional excitation rates from excited states by low energy (few eV) electrions, such as:

  $$N_2\ (A) + e \longrightarrow N_2\ (C) + e$$

- High resolution spectra with nanosecond time resolution of air irradiated by intense particle beams.

5.2 Air Chemistry

5.2.5 Equilibration Times

Issue: What is the equilibration time of energetic (~15 eV) electrons? These are too low in energy to ionize. Many secondary electrons cascade through this energy range of more complicated chemistry before thermalizing. The time can be $\sim 10^{-10}$ sec.

Priority: Modest. Probably entails moderate quantitative changes to early time conductivity.

Research Needed:

- Cross section data for these energetic electrons on dominant species (N_2, O_2 ...)
- Direct early time reaction rate data.
- Estimates of importance of this effect.

Options:

- Analytic estimates of importance - high promise
- Direct quantum mechanical cross section calculations and kinetic Boltzmann calculations assuming reasonable cross sections - promising.
- Experiments:
  1) Very early time and/or extremely high temperature rate coefficients - very difficult - low promise.
  2) Extend electron beam experiments to lower energies - less difficult - higher promise.

Significant Parameters:

- Effective rate coefficients as a function of mean electron energy and E-field strength
- Mean electron energy as function of time.

5.2 Air Chemistry

5.2.6 Reaction Rates of Species as a Function of Vibrational State

Issue: In a non-equilibrium state, one cannot assume equilibrium kinetics; consequently, finite rate kinetics are required to accurately describe the species concentration and energy state of the system. If an analysis of the signature of the beam trace is required, one must describe in detail the vibrational states (one can assume for now rotational equilibrium at atmospheric pressures).

Priority: Medium.

Research Needed: Literature surveys, experimental measurements and theoretical predictions must be made to determine the reaction rates as a function of vibrational states.

Options: Current plasma kinetic packages for CO_2 EDL's have a significant number of reaction rates as a function of vibrational states. Certain plume finite rate chemistry packages also treat many species considered as a function of vibrational states.

Significant Parameters:

- o Temperature
- o Pressure

5.2 Air Chemistry

5.2.7 Rotational Non-Equilibrium

Issue: At low pressure (10-30 Torr) certain rotational relaxation rates are slow enough so that rotational equilibrium is a bad assumption. An accurate representation of the excited states must include treating the rotational states as a single species. Signature analysis will require this more complete treatment of rotational states.

Priority: Low. The rotational non-equilibrium is noted in the HF laser cavity, but is not as significant for the DF laser.

Research Needed: Literature surveys, experimental measurements and theoretical modeling of the reaction rates must be conducted.

Options:

- Investigate rotational non-equilibrium work performed for HF chemical lasers for the Air Force Weapons Laboratory. The modeling concept could be utilized.
- Not all species should be considered.
- Only low pressures at high altitudes should be considered.

Significant Parameters: Reaction rates as a function of rotational and vibrational states as well as pressure and temperature should be considered.

5.2 Air Chemistry

5.2.8 Non-Equilibrium Chemistry

Issue: What are the effects of non-equilibrium chemistry upon channel formation.

Priority: Uncertain. Non-equilibrium internal energy or particle velocity distributions affect the rate at which gas dynamic disturbances grow. Shock waves propagating radially are manifestations of collisional redistribution of energy deposited in the gas. This phenomenology may be important in predicting allowed pulse and "bolt" spacing.

Research Needed:

- Documentation of reactions and non-equilibrium phenomena which persist over time scales longer than one pulse ($\sim$10 nsec) and shorter than or comparable with canonical gas dynamic response times ($\sim$100 μsec).
- Investigation of the effect of nonequilibrium distribution of rotational vibrational and excited state energy upon radial propagation of gas disturbances and the density fields (and conductivity distributions) established thereby.

5.3 Instabilities

The subject of macroscopic and microscopic beam driven instabilities in real-time in the case of endo-atmospheric (CPBW) systems was reviewed and the following topics are to be reported herein.

(5.3.1) Scaling laws for hose instability

(5.3.2) Scaling laws for 2-stream instability

(5.3.3) Filamentation (Good or Bad?)

(5.3.4) Character of beam equilibria

(5.3.5) "Other" instabilities

(5.3.6) Laser beam prepared channels

A variety of technical issues arose in the discussion of these topics, and those which require continuing research effort and support are now reported in the following specific issue-statements.

5.3 Instabilities

5.3.1 Resistive Hose Instability

Issue: Transverse displacement of a beam in a resistive medium may lead to growing transverse oscillations. Current theoretical models suggest that such disturbances will convert back towards the beam tail as the displacement grows in amplitude. Improved models and experimental data are needed to give more realistic scaling laws. Specifically, better understanding is needed of how "hose" instabilities scale with particle type (e.g., protons - low gamma longitudinal dispersion effects on hose), gas density, channel density gradients, current.

Priority: Very high. This is a critical phenomena - scaling laws will have significant impact on beam applications.

Research Needed:

- o Low - gamma effects (for protons and ions)

  1) longitudinal temperature scaling, i.e., the longitudinal energy spread.
  2) improved real-time electromagnetic field algorithms, e.g., precursor field effects.
  3) formal derivation of and/or improvements on distributed mass model to define the limits of validity of such models.

- o Simulation studies

  1) Test paraxial approximations.
  2) Check sensitivity to more realistic beam equilibrium and channel distributions.
  3) Check validity of frozen field approximation in the context of hose time scales.

Options:

1) High current experiments to complement ATA for current scaling.
2) Critical experiments with proton beams are not possible until significant advances in proton accelerators have been achieved. However, it may be possible to study low-gamma affects through low energy, high current electron beam experiments.

5.3 Instabilities

5.3.2 Scaling of Two-Stream Instability

Issues:

- o Scaling laws for instability growth rates for finite temperature beams in collisional plasmas are not known. The following effects need to be taken into account:

  1) transition between kinetic and hydrodynamic regimes,
  2) pinched beam equilibria (includes both beam "temperature" and finite geometry).

- o In the non-linear regime, the following must be determined:

  1) saturation mechanisms and their effect on the beam and background plasma,
  2) possible remedies.

- o Experiments are required which not only provide gross evidence for existence of instabilities, but also yield scaling laws.

Priority: High

Research Needed:

- o Numerical and analytical studies of two-stream instabilities in charged particle beams in infinite homogeneous medium to understand the transition between hydrodynamic and kinetic regimes and its effect on the collisional stabilization of the mode. Comparison of electron beams and proton beams is desirable.
- o Extension of the infinite homogeneous linear theory to include the effects of realistic pinched beam equilibria and finite plasma column principally through numerical techniques and analytical methods when appropriate.
- o Identify dominant non-linear mechanisms depending on time scales, energy densities, and linear spectral consideration. Assess the effects of these mechanisms on the beam and plasma evolution by means of crude analytic laws and by simulation techniques.

5.3 Instabilities

5.3.2 Scaling of Two-Stream Instabilities (Cont.)

- o Define experimental diagnostics in order to obtain unique signatures of the instability beam differential energy spectra, background plasma parameters, e.g., spatially resolved plasma density and temperature. Transient beam plasma systems are inherently very noisy. It is important to develop spectroscopic techniques for remote sensing of the instability with good S/N ratio. Examples might be secondary emission, incoherent scatter, holographic interferometry and atomic spectrographic techniques.

<u>Options:</u> Identify those parameter regimes for which the 2-stream instabilities will be detrimental to beam over long distances and beam target interactions.

<u>Significant Parameters:</u>

- o Unfolding instability - in its presence it is unlikely that significant energy densities will propagate over long distance.
- o Two-stream instability - it may play an important role during beam - target interactions.

PROPAGATION

5.3 Instabilities

5.3.3 Filamentation and Beam Particle Distributions

Issues: Is beam filamentation a phenomenon which could be an overall stabilizing influence on the propagation of high power density electron beam pulses in the atmosphere?

Background: Electron-beam filamentation can be viewed under proper conditions as a very efficient mode of propagation of the beam with a minimum of energy losses and a maximum of power deposition density on a target (TW/cm^2). Experiments suggest that electron beam "filaments"

- o are current neutralized and thus are not deflected by kilogauss magnetic fields
- o transport high levels of current and power densities (0.1 - 1 TW/cm^2 with a generator energy of a few kilojoules)
- o develop strong coupling to solid targets
- o can propagate through cracks (1 μm wide) in solid materials by assuming a sheath structure
- o are most effective in collectively accelerating ions
- o can be clustered together to form bunches (300 μm diameter) which are free from hose and two-stream instabilities
- o are useful to observe the distribution of the collectively accelerated ions inside a filament (e.g., the high energy ions -> 3 MeV ions accelerated by 300 KeV electrons - are concentrated at the periphery of the filament).
- o do not suffer appreciable attenuation ("tip" erosion) with 1 - 10 μm filament diameters when propagating over a three meter path length.

Research Needed: Theoretical and experimental work on this important method of beam propagation.

5.3 Instabilities

5.3.3 Filamentation and Beam Particle Distributions (Cont.)

Options: An electron beam with E $\geq$ 400 keV and current $\geq$ 100 kA can be produced by plasma focus discharges in a high density state. The plasma focus generator is an extremely flexible, compact, cost effective, and reliable device with verified scaling laws from 1 kJ to 400 kJ

Significant Parameters: Experiments with the plasma focus and other systems indicate that electron-beam filaments can be manufactured, focused, and compressed by a convenient choice of the system parameters.

5.3 Instabilities

5.3.4 Equilibrium Beam and Return Current Characteristics

Issues: An approximate knowledge of beam space and velocity profiles must be obtained to determine beam stability properties. The issue must be addressed separately for low and high altitudes of propagation and for electrons and protons, as scaling may be different for each case. Channel return current and conductivity profiles are particularly important to hose and filamentation.

Priority: Intermediate. Knowledge of beam equilibrium characteristics need to be developed only fast enough to keep pace with increasing sophistication of instability models.

Research Needed:

- Development and application of computer codes for studying beam propagation
- Development of good diagnostics and high energy, controlled beam sources.

Options:

- Accelerator design codes may yield beam distributions near the accelerator
- PIC codes with rudimentary Monte Carlo are effective for evaluation of beams over short distances. Real Monte Carlo codes may be useful if self-fields can be included properly.
- Fokker-Planck methods may allow addressing of electron straggling.

Significant Parameters:

For a major experiment the electron energy beam must exceed 100 MeV in order to take account of straggling. Minimum energy for the ion beam is also high.

5.3 Instabilities

5.3.5 "Other" Relevant Instabilities

Issues: Although a popular consensus exists that the hose, 2-stream and filamentation instabilities are the only ones important to propagation, it may be that "other" significant instabilities may exist, but have not yet been considered.

Priority: Low. Since it is not likely that there are "other" important instabilities, work should be carried out only as important new insights arise.

Research Needed: Such "other" instabilities are most likely to be found in the course of other research. Once found, they should be pursued by modest theory and if necessary, by experimentation. Possible "other" instabilities include:

- o ion-acoustic and drift instabilities
- o secondary modulational and parametric instabilities.

Radiative processes should also be considered, both for their own sake and as possible beam-diagnostic tools.

PROPAGATION

5.3 Instabilities

5.3.6 Laser Formation of Air Channels

Issues: Can the effect of certain instabilities be ameliorated by using a laser to create an ionized pathway (channel) thereby forcing the particle beam to follow this trajectory?

Research Needed:

- Determination of the necessary laser-driven plasma density in the pathway
- Laser power/energy to create pathway
- Demonstration experiments such as
  1) channel-pathway formation processes
  2) beam guidance phenomena

Unique Capabilities;

Assuming a high power laser is required, the 12 TW Nd: glass laser at the National Laser Facility of the University of Rochester is available as a user facility to qualified scientists for demonstration experiments.

5.4 Plasmoid Propagation

Issues: Can propagation via plasmoids be used to couple energy from the accelerator to the target? This requires the determination of the trajectory, stability and volumetric growth of the plasmoid/beam for a given range in order to determine accelerator plasma preparation requirements from the on-target requirements. Few experiments or theoretical analyses have been performed for the appropriate plasma parameter ranges. Depending upon the self-pinch effectiveness, two important regimes of beam particle energy have been identified: plasmoid at high energy, and space charged neutralized ion beam at low energy.

Priority: Very high. Propagation of the beam as a plasma is a key determinant of effective range. Self-focusing effects may be required to achieve desired range, particularly if the accelerator emittance cannot be reduced below present estimates.

Research Needed: Theoretical models and experiments (in both the laboratory and the space shuttle) to address the key physics questions:

- What is the plasmoid trajectory?
- Is the plasmoid MHD stable? If unstable, is the plasmoid fragmented and dispersed in a flight time?
- Is the plasmoid micro-unstable? If yes, what are the growth rates and saturated states?
- Is there sufficient heating to disperse the plasmoid in a flight time?
- Can currents in a plasmoid reduce its spread? Can these currents be sustained against Spitzer and anomalous resistivity?
- What is the effect of the geomagnetic field? - Soak-in time, etc.
- Will currents themselves drive instabilities? What is their effects on heating, etc.?
- What are the interactions with ionosphere and background neutrals that are important?

5.4 Plasmoid Propagation (Cont.)

Options:

- o Analytic theory of propagation of idealized plasmoids/beams.
- o Subscale experiments for analyzing specific effects or combinations of effects.
- o Simulations of idealized plasmoids/beams to analyze specific effects or combination.
- o Formation of heuristic/analytical model containing information from above options.
- o Comparison of models with experiments and larger scale simulations
- o Analysis can be done by treating a succession of progressively more sophisticated idealizations

Idealizations:

Parallel ion orbits with T = 0

Finite emittance with T = 0

Finite emittance with finite T.

Parallel ion orbits with T = 0 and with J(r) at t = 0

Finite emittance with T = 0 and with J(r) at t = 0

Finite emittance with finite T and with J(r) at t = 0

Significant Parameters

- o Energy per particle
- o Beam diameter
- o Beam density
- o Pulse length
- o Emittance
- o Temperature
- o Internal currents
- o Degree of charge neutrality
- o Radiation environment
- o Geo-magnetic and geo-electric fields
- o Background neutrals and plasma

VI. BEAM-MATERIALS INTERACTIONS

6.1 Preface

The participants in the workshop dealing with issues in beam-materials interactions reported their views along three major lines:

(6.2) Radiation Transport

(6.3) Materials Response

(6.4) Beam Sensing

Radiation transport is important because it helps to understand energy coupling (to both structural and electronic materials) as well as energy release from targets. The latter could serve as a key input for pointing, tracking, and target discrimination. In addition to structural materials, the response of electronic devices, chemically-reactive materials, and nuclear warhead materials are all important since they could result in lower threshold energies for target kill than for structural materials. Sensitive mechanisms for sensing beam trajectories and target interactions are sought since without them, particle beam weapons will be at a major operations disadvantage relative to explosive (or even laser) weapon systems. Finally, it should be noted that while electromagnetically-transparent materials were not considered at the workshop, it should not be construed that they are unimportant.

6.2 Radiation Transport

6.2.1 Nuclear Interaction Models

Issue: What is the character of the nuclear radiation (i.e. neutrons, gamma rays) emitted from thick targets due to high energy ion bombardment?

Research Needed: Development and validation of nuclear interaction models describing

- o secondary particle production,
- o partial cross sections,
- o energy spectra,

for ion beam bombardment of various target materials.

Significant Parameters:

- o Type of ion: p, d, t, Li, plus heavier species.
- o Energy of ion: 50 Mev to several hundred Mev.
- o Target methods: low to high Z (e.g., Al, Fe, U).

6.2 Radiation Transport

6.2.2 Collective Effects in Material Interactions

Issue: What is the nature of the collective effects of high energy beams in their interaction with target materials? To be considered are multiple-pulse beams with complex energy spectra and the plasmas and beam bunching effects which result from such beams.

Research Needed: Theory and experiments to elucidate:

- plasma formation during the beam target interaction, including thresholds, due to:

  1) multiple pulses

  2) a beam with a complex energy spectrum

- transport coefficients for the plasmas produced
- the extent to which the plasmas alter the signatures of the interaction
- bunching, clustering and self-pinching effects on a beam during passage through a single or multiple layer target
- the intensity dependence of the onset of this collective effect

6.2 Radiation Transport

6.2.3 Multimaterial Transport Models

Issue: For semiconductor devices characterized by multiple thin layers of materials, is it valid to use the normal approach to radiation transport which is to assume no significant interaction between the effects produced on nearby layers of materials?

Research Needed: Theoretical work is needed to

- broaden current capabilities to include boundary and edge effects
- develop models to simplify description of the process.

Experimental data are needed to

- guide development of theory and models of the interaction
- validate the models

Single particle transport, nuclear recoil, and collective effects should all be considered.

Significant Parameters:

- Distance scale of the effects
- Model size, accuracy, speed, and data requirements
- Full range of beam characteristics (energy, pulse length, spectrum)

6.3 Materials Response

6.3.1 Chemically Reactive Materials

Issue: What is the energy deposition required to produce ignition (burning, deflagration, detonation) of a target's high explosive propellants?

Research Needed: Theory and experiments to

- o determine ignition characteristics of samples exposed to low (0.1 to $1A/m^2$) and high ($> 10kA/cm^2$) currents for single and multiple pulse beams.
- o develop equations describing the process including coupled hydrodynamics/heat transfer/chemical reactions.

Significant Parameters:

- o Sample size (tens to hundreds of pounds)
- o Nature of the confinement of the chemically reactive material.

Unique Capabilities: The DOE nuclear weapon laboratories are the only logical location to plan for these experiments.

6.3 Materials Response

6.3.2 Structural Materials

Issues: What is the response of structural materials to high energy electron and proton beam deposition (> 1KJ/gm)?

Research Needed: Studies and experiments are needed to determine

- o relevance of past work in nuclear vulnerability to this problem area
- o characterization of beam parameters from development of diagnostics for existing useful proton and intense relativistic electrom beam machines
- o shock phenomena from small diameter beams
- o multi-pulse effects (time separation < 1ms)
- o validity of codes describing material response using currently available machines (can match energy deposition and therefore peak pressure but cannot match depth dose, nuclear reaction, or beam temperature)

Diagnostics are needed for measuring energy depositicn vs peak pressure, especially at high energies.

Significant Parameters:

- o Dose range (10^{-2} to > 10^{3} J/gm)
- o Multiple pulse effects
- o Beam size small compared to target
- o 2 and 3D effects
- o Nonlinear, multi-phase effects

BEAM-MATERIALS INTERACTION

6.3 Materials Response

6.3.3 Nuclear Warhead Materials

Issues: What is the nature of the thermo-mechanical damage (spallation) to and neutron production from fissile materials and others in the delivery vehicle as a result of irradiation by high energy density particle beams?

Research Needed: Experiments are needed to determine

- the shock pressures produced in fissile materials (U^{235}, U^{238}, Pu^{239} and their alloys) by well-characterized electron and ion beams
- the spall strength of fissile materials
- the Gruneisen coefficient of such materials
- the neutron production by high energy e, p, d, t and heavier ion beams upon interaction with the fissile materials and other elements used in nuclear warheads and their delivery systems
- the spectra of the neutrons produced

Unique Capabilities:

- LBL's Bevelac for p, d and heavier ions in range of 100 Mev to several Gev
- Stanford's Mark III linac for electrons in range of 100-500 Mev

6.3 Materials Response

6.3.4 Electronic Devices

Issues: As a result of exposure to high energy particle beams, electronic components exhibit dose and dose-rate effects in the form of errors induced in stored information, latch-up of circuits, and component damage. What are the threshold levels at which these effects begin for various types of integrated circuit devices?

Research Needed: Theory and experiments to determine

- the spectra of energy deposited in the microscopic volumes of integrated circuits
- the threshold for soft-error (circuit latch-up; errors induced in memories) production in LSI, VLSI, and radiation hardened devices
- the nature of rate-dependent effects (soft and hard errors) in cases of exposure to high flux levels of particle beams

Options:

- Design of integrated circuits to minimize one dimension of the charge collection region
- Avoidance of SiO_2 in silicon devices to minimize circuit latch-up; i.e., use Si MESFETs
- Use materials with higher thresholds, i.e., use GaAs MESFETs

Significant Parameters

- Threshold dose and dose rate
- Type of particle in beam
- Particle energy
- Size and design of integrated circuit

6.4 Beam Sensing

6.4.1 Radiation Signature From Targets

Issue: Can the infrared, x-rays, gamma rays or neutron radiation from a high energy particle beam interacting with the target be detected and interpreted with confidence as a target hit and destruction signature? What is the background radiation from the target?

Research Needed: Experimentation and analysis to determine

- o intensity and spectra vs beam energy of infrared, carbon x-rays, gamma rays, K-shell characteristic emission from high Z materials, and neutrons emitted from irradiated target
- o the development of sensors for detecting this radiation (if development is indicated by systems analyses)
- o the capability of the sensors to discriminate against strong, nearby, unwanted signals (e.g., IR detectors which can discriminate between target radiation and atmospheric radiation caused by the intense beam)
- o ways to manipulate these various signatures to also achieve target vs background discrimination
- o background radiation from the target.

Options: IR, x-rays, gamma rays, neutrons, background radiation

Significant Parameters:

- o Type of particle beam
- o Nature of target
- o Beam intensity
- o Other system parameters

6.4 Beam Sensing

6.4.2 Microwave/Optical Detection

Issue: Can microwave and/or optical phenomena be used to sense the trajectory of the high energy particle beam for feeding back to the closed loop pointing and tracking system?

Research Needed: Theoretical studies and experiments to determine

- if Helmholtz or other instabilities exist at the beam boundary (smooth or ragged) which could couple to optical or microwaves
- emission spectrum from the beam vs time
- if excited radiative states of the H° or unneutralized H^{-} emerge from the stripper
- new ideas, especially for use with neutral beams

Options:

- Electro-optics - passive/active - not all weather
- Microwaves (1-100 MW, 2-10 GHz) - scatter off channel instabilities
- Combine acquisition with beam tracking
- Seeding of ion beam with radiating species
- Radiation from excited states of H atoms
- Laser scattering from excited ions

Significant Parameters:

- Magnetic field effects
- Beam energy
- Degree of neutralization of beam
- Beam edge instabilities

VII. LIST OF ATTENDEES

Dr. John Adamski
P.O. Box 3999
Boeing Aerospace Co.
Seattle, WA 98124

Dr. Tony Armstrong
SAI
1200 Prospect St.
La Jolla, CA 92037

Dr. Donald Amush
TRW
Redondo Beach, CA 90278

Dr. John Bayless
DARPA
1400 Wilson Blvd.
Arlington, VA 22207

Dr. James Benford
Physics International
2700 Merced St.
San Leandro, CA 94557

Dr. Winston H. Bostick
Stevens Institute of Technology
Hoboken, NJ 07030

Dr. Howard E. Brandt
Department of the Army
Harry Diamond Labs
2800 Powder Mill Road
Adelphi, MD 20783

Dr. Richard J. Briggs
Lawrence Livermore Labs
P.O. Box 808
Livermore, CA 94550

Capt. Gary Dean Cable
AFWL/IN
Kirtland AFB, NM 87117

Dr. Neal J. Carron
Mission Research Corp.
P.O. Drawer 719
Santa Barbara, CA 93102

Dr. Phil Champney
Physics International Co.
2700 Merced St.
San Leandro, CA 94577

Dr. Ralph Cover
R&D Associates
Marina Del Rey, CA 90291

Dr. M. Cowan
Sandia Labs
P.O. Box 5800
Albuquerque, NM 87185

Dr. James L. Cox, Jr.
Old Dominion University
Hampton Blvd.
Norfolk, VA 23508

Dr. Dan Dakin
Physics International Co.
2700 Merced St.
San Leandro, CA 93557

Dr. D. K. Davis
Westinghouse R & D Center
1310 Beulah Rd.
Pittsburgh, PA 15235

Dr. William W. Destler
University of Maryland
Electrical Engineering Dept.
College Park, MD 20742

Dr. Wesley O. Doggett
N.C. State University
P.O. Box 5342
Raleigh, NC 27650

Maj. Harald Dogliani
AFWL/NTYP
Kirtland AFB, NM 87117

Dr. Donald Eccleshall
Ballistic Research Lab.
Aberdeen Proving Ground, MD 21005

Dr. Kent R. Edwards
Science Applications, Inc.
8400 Westpark Drive
McLean, VA 22102

Dr. Rickey J. Faehl
Los Alamos Scientific Lab
Los Alamos, NM 87545

Dr. R. Leon Feinstein
Science Applications, Inc.
5 Palo Alto Square,
Palo Alto, CA 94304

Mr. Harold W. Funk
U.S. General Accounting Office
Washington, D.C. 20548

Dr. George Gamota
OUSDRE (R&AT)
The Pentagon
Washington, D.C. 20301

Dr. George H. Gillespie
Physical Dynamics Inc.
P.O. Box 1883
La Jolla, CA 92038

Dr. Brendan B. Godfrey
Mission Research Corp.
1488 San Mateo S.E.
Albuquerque, NM 87108

Dr. Martin V. Goldman
Univ. of Colorado
Boulder, CO 80329

Dr. Pierre Grand
Brookhaven National Labs.
Upton, NY 11973

Dr. Steward E. Graybill
Harry Diamond Labs
2800 Powder Mill Road
Adelphi, MD 20783

Dr. John Guillory
Theoretical Physics Div. JAYCOR
205 S. Whiting St.
Alexandria, VA 22304

Dr. Zaven G. T. Guirangossian
TRW, Defense & Space Systems Group
One, Space Park
Redondo Beach, CA 90287

Dr. Ward Halverson
Spire Corp.
Patriots Park
Bedford, MA 01730

Dr. Brian Hanson
AF Weapons Lab.
Kirtland AFB, NM 87117

Dr. Robin Harvey
Hughes Research Lab.
3011 Malibu Cyn Rd.
Malibu, CA 90265

Dr. Larry J. Havard, Jr.
Ballistic Missile Defense, Adv. Tech. Ctr.
P.O. Box 1500
Huntsville, AL 35807

Dr. T. D. Hayward
Los Alamos Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

Maj. James H. Head
Foreign Technology Division
Wright-Patterson AFB, OH 46433

Dr. George Heffernan
Office of Energy Programs
George Washington Univ.
Washington, DC 20052

Capt. Robert F. Hoeberling
FTD/TQTD
Wright-Patterson AFB, OH 45433

Dr. Owen C. Hofer
Box 1103
Huntsville, AL 35802

Dr. Charles M. Huddleston
Naval Surface Weapons Center
White Oak Lab; R401
Silver Spring, MD 20910

Dr. Robert O. Hunter, Jr.
Western Research Corp.
8616 Commerce Ave.
San Diego, CA 92121

Dr. Robert J. Johnston
Science Applications, Inc.
5 Palo Alto Square
Palo Alto, CA 94304

Dr. A. L. Jokl
USAMERADCOM
Ft. Belvoir, VA 22060

Dr. David Judd
Lawrence Berkley Labs.
University of California

Dr. Simon Kassel
The Rand Corporation
2100 M. Street, NW
Washington, D.C. 22037

Dr. Harold Kaufman
Physics Dept.
Colorado State Univ.
Fort Collins, CA 80523

Dr. R. N. Keeler
Univ. of California
P.O. Box 808
Livermore, CA 94550

Dr. Doug Keeley
Science Applications, Inc.
5 Palo Alto Square
Palo Alto, CA 94304

Dr. Alan Kehs
Harry Diamond Labs
2800 Powder Mill Rd.
Adelphi, MD 20783

Dr. George Kemeny
Westinghouse Electric Corp.
1310 Benlah Rd.
Pittsburgh, PA 15235

Dr. M. Kristiansen
Dept. Electronic Eng.
Texas Tech. Univ.
Lubbock, TX 79409

Dr. Hans Kruger
Lawrence Livermore Lab.
P.O. Box 808
Livermore, CA 94550

Dr. Erich E. Kunhardt
Texas Tech. Univ.
Lubbock, TX 79409

Dr. Edward P. Lee
Lawrence Livermore Lab.
P.O. Box 808
Livermore, CA 94550

Dr. Thomas Lockner
Naval Research Lab.
Overlook Ave,
Washington, D.C. 20375

Dr. Bernard A. Lippmann
Physics International Co.
2700 Merced St.
San Leandro, CA 94577

Dr. Robert Lontz
Army Research Office
P.O. Box 12211
Research Triangle Park, Durham, NC 27709

Dr. Donald C. Lorents
SRI International
333 Ravensworth Ave
Menlo Park, CA 94025

Dr. Lawrence H. Luessen
Naval Surface Weapons Center.
Dahlgran, VA 22401

Dr. Eugene McGuire
Sandia Laboratory
Albuquerque, NM 87185

Dr. Raymond Missert
Calspan Corp.
P.O. Box 235
Buffalo, NY 14221

Dr. G. Marshall Molen
Old Dominion Univ.
Electrical Eng. Dept.
Norfolk, VA 23508

Dr. Martin Nahemow
Westinghouse Elec. Co.
1310 Beulah Rd.
Pittsburgh, PA 15217

Dr. Vittorio Nardi
Stevens Inst. of Technology
Hoboken, NJ 07030

Dr. John Nation
Cornell Univ.
Phillips Hall
Ithica, NY 16833

Dr. Barry S. Newberger
Intense Particle Beam Theory Group
Los Alamos Scientific Lab
Los Alamos, NM 87545

Dr. Craig L. Olson
Plasma Theory Div
Sandia Labs
Albuquerque, NM 87185

Dr. Ronald E. Olson
SRI International
Molecular Physics Lab
Menlo Park, CA 94025

Dr. John A. Parmentola
MIT, Dept. of Physics
77 Mass Avenue
Cambridge, MA 02139

Dr. Richard M. Patrick
Avco Everett Resh Lane
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Gerald J. Peters
Naval Surface Weapons Center
White Oak Lab
Silver Spring, MD 20910

Dr. Arthur V. Phelps
Joint Inst for Lab Astrophysics
University of Colorado
Boulder, CO 80309

Dr. Armand M. Pelletier
BMDATC-D
Box 1500
Huntsville, AL 35807

Dr. A. W. Possner
Westinghouse Elec Cor.
1310 Beulah Rd.
Pittsburgh, PA 15235

Dr. James R. Powell
Brookhaven National Lab
Dept. of Nuclear Energy
Upton, NY 11973

Dr. Sidney Putnam
Physics International Co.
2700 Merced St.
San Leandro, VA 94577

Dr. Allen Ramrus
Maywell Labs.
9244 Balboa Ave.
San Diego, CA 92123

Dr. Dennis A. Reilly
Avco Everett Research Lab.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Martin P. Reiser
University of Maryland
Dept. of Physics
College Park, MD 20742

Dr. Charles W. Roberson
Naval Research Lab
4555 Overlook Ave.
Washington, D.C. 20375

Dr. Thomas G. Roberts
Directed Energy Directorate
Army Missile Lab
U.S. Army Missile Command
Redstone Arsenal, AL 35809

Dr. Raymond S. Robinson
Physics Dept.
Colorado State Univ.
Fort Collins, CO 80523

Dr. C. W. Von Rosenberg, Jr.
Avco Everett Research Lab.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Normal Rostoker
Univ. of California - Irvine
Dept. of Physics
Irvine, CA 92717

Dr. Milos Seidl
Physics Dept.
Stevens Inst. of Technology
Hoboken, NJ 07030

Dr. I. A. Sellin
Univ. of Tenn.
P.O. Box X
Oak Ridge, TN 37830

Dr. William R. Shanahan
Los Alamos Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

Dr. Ian D. Smith
IAN SMITH INC.
3115 Gibbons Dr.
Alameda, CA 94501

Dr. Kenneth S. Smith
JAYCOR
360 South Hope Ave.
Santa Barbara, CA 93105

Dr. A. G. Stewart
Harry Diamond Labs
2800 Powder Mill Rd.
Adelphi, MD 20783

Dr. C. M. Stickley
THE BDM CORPORATION
7915 Jones Branch Drive.
McLean, VA 22102

Dr. David C. Straw
AF Weapons Lab
Kirtland AFB, NM 87117

Dr. Donald Sullivan
Mission Research Corp.
1400 San Mateo, SE
Albuquerque, NM 87108

Dr. James R. Thompson
Austin Research Association
1901 Rutland Dr.
Austin, TX 78758

Dr. S. M. Trujillo
IRT Corp.
7650 Convoy Court
San Diego, CA 92111

Dr. M. S. Uberoi
University of Colorado
Boulder, CO 80329

Dr. John L. Uglum
Austin Research Association
1901 Rutland Dr.
Austin, TX 78758

Dr. Olav T. Vik
Kaman Sciences Corp.
1500 Garden of the Gods Rd.
Colorado Springs, CO 80907

Mr. Ihor M. Vitkovitsky
Naval Research Lab.
Washington, D.C. 20375

Dr. John Walsh
Dartmouth College
Wilder Lab. Physics Dept.
Hanover, NH 03755

Dr. Laurence B. Warner
Los Alamos Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87544

Lt. Col. Donald Washburn
AF Weapons Lab/NTYP
Kirtland AFB, NM 87117

Dr. Eric Wenaas
JAYCOR
P.O. Box 370
Del Mar, CA 92014

Dr. Jack Wilson
University of Rochester
250 East River Road
Rochester, NY 14623

Dr. David Woodall
University of New Mexico
Dept. of Chem & Nuc Eng
Albuquerque, NM 87131

Dr. William E. Wright
Lawrence Livermore Lab.
P.O. Box 808
Livermore, CA 84550

Dr. Paul Rotwell
AF Geophysics Lab.
LG Hanscom AFB, MA 01730

Dr. Arthur Diness
Office of Naval Research
Dept. of the Army
Arlington, VA 22217

Dr. John L. Harrison
Maxwell Labs.
9233 Balboa Ave.
San Diego, CA 92123

Dr. Peter McNulty
AF Geophysics Lab.
LG Hanscom AFB, MA 01730

Dr. Carl Liader
McDonnell Douglas Corp.
St. Louis, MO

Dr. Michael A. Greenspan
McDonnell Douglas Corp.
St. Louis, MO

Dr. Fred Rothwarf
US Army Electronics R&D Command
Fort Monmouth, NJ 07703